

BIO-BASED LUBRICANT SELECTION FOR METAL CUTTING OPERATIONS USING MADM TECHNIQUE

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ABSTRACT

Increased concerns about potential environmental hazards, due to mineral oil based lubricants foster the use of vegetable oil as base oil in various metal cutting operations. The selection of vegetable based oil that caters to the need for all metal cutting operations is a complex task. Selection of appropriate base oil for a specific operation depends on a number of diverse criteria or attributes. In this paper, nine attributes such as viscosity index, flash point, pour point, oxidation stability, availability, cost, anti-wear, extreme pressure properties, coefficient of friction and fourteen alternative vegetable base oils were considered for decision making. The preference index for ranking of base oil is computed by using MADM technique, and it was suggested that palm oil is more significant base oil to be used for further formulation. In this paper, subjective as well as objective weights are compared. Subjective preferences are evaluated using AHP and integrated weights are also calculated. However, castor oil, jatropha oil, rapeseed oil and coconut oil can also be strived with an appropriate set of additives, in order to render it a suitable lubricant for specific metal cutting operation.

KEYWORDS: Analytical Hierarchy Process (AHP), Multi Attribute Decision Making (MADM), Vegetable Oil & Metal Cutting

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1. INTRODUCTION

The mineral based oils, hardly meet the requirement of metal cutting operations without the support of anti-wear and extreme-pressure additives. Besides, being environment friendly, vegetable based lubricants have inherent lubricity, polar nature, high viscosity index and biodegradability. Lubrication plays a very important role during the metal cutting process. Tribology consists of boundary friction, which is associated with all metal cutting processes. At boundary lubrication zone, the oil film is very thin, so there are possibilities of asperities contact. To create effective boundary lubricant, it is very essential to know various tribological behavior of base oil. Mineral based metal cutting oils are found to be toxic and non-biodegradable in nature. The natural consumption of resources and wastage, generated after cutting with mineral-based oil are very difficult to degrade.

An ever increasing issue of biodegradability and global energy crises fosters the need of replacing mineral based oils by the bio-lubricants [1-2, 6]. The physical and chemical properties of the base oil also affects the tool life, surface finish, force and power requirement, disposability into the environment, toxicity of lubricant etc. [15].

Investigations have been carried out by various researches in formulation and evaluation of tribo-mechanical properties of vegetable based lubricating oils such as sunflower oil [3-4], coconut oil [5], cotton seed oil [7], neem and castor oil [8], mustard seeds oil [9], Jatropha-based oil [10], palm oil [11] for various metal cutting operations. These

oils exhibit good anti-wear properties, and no harmful gases produced to the environment [2, 6]. Apart from cutting fluids, coconut oils were also evaluated as a boundary lubricant for its performance as an engine oil in auto-rickshaw [5]. Agrawal et al., [7] studied wear behavior of M2 steel using Cotton seed oil and correlate with drilling process. Srivyas and Charoo [6] did comparative study of various bio-based lubricants and mineral based oils in regard to their performance characteristics, lubrication mechanism, test methodologies and tribological effects. Gajrani and Sankar [14] reviewed physicochemical properties, composition and applications of individual vegetable oil as a metal cutting lubricant. Applicability of vegetable oil-based cutting fluid of various ferrous metals was evaluated and reviewed [14–15].

The selection of base oil of biological origin for the formulation of metal cutting lubricants that caters the need of all rheological and tribological properties, is a complex task. Selection of appropriate base oil depends on a number of diverse criteria or attributes. These attributes include rheology of lubricant, tribo-properties, additive compatibility, environmental conditions, type of tribo-system, stability and cost as depicted in figure 1. Considering various sets of requirements, needless to say that base oil selection, that too of vegetable/Bio base is of prime importance. Till now, trial and error has probably played a larger role than any other single attribute in base oil selection, pertaining to the specific application. Through the combination of testing and experience, users have learnt that which base oil will suit well for metal cutting applications? Based on the product description, process characteristics, operating requirements lubricant manufacturer use to select bio-base oils that meet the users' requirements.

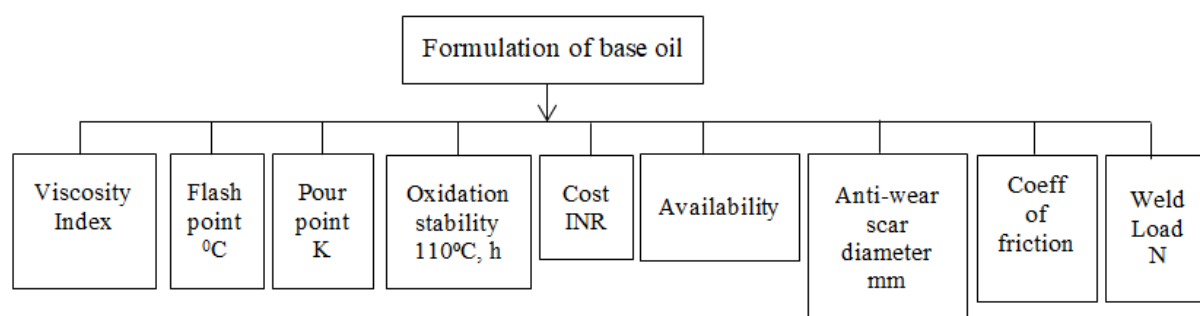


Figure 1: Diverse Criteria for Formulation of Base Oil.

In base oil selection, not much scientific method is available for assessment of base oil, quantitatively and qualitatively. An AHP technique is used by several researchers for decision making problem [12]. In this work, authors made an attempt to select appropriate bio-based base oil by using multi attribute decision making model. The values for objective weights were taken from open literature and various investigations carried out by researchers on vegetable base oil [3–20].

2. MULTI-ATTRIBUTE DECISION-MAKING MODEL (MADM)

MADM is employed for the selection of appropriate alternative from finite number of alternative corresponding to their attributes. MADM is the efficient method to find out the effective alternative for the desired application. Multi-Attribute Decision-Making model consist of four parts such as alternative, attribute, objective or selective weight of each attribute and computation of preference index with respect to the attributes.

2.1 Problem Modeling

Alternatives and attributes under consideration are as given in table 1.

Table 1: Properties of Vegetable Based Oils

Vegetable Base Oil	Properties of Vegetable Based Oils								
	VI [22–23]	FP (°C) [22–23]	PP (K) [22–23]	OS (110°C,h) [21–22]	C/lit (INR)	A	AWSD (mm) [5,23]	COF (μ) [5,20,23]	WL (N) [5]
Castor Oil	220	260	246	1.2	145	Above average	0.15	0.09	2158
Groundnut Oil	214	249	270	6.5	250	Very high	0.63	0.04	1200
Rapeseed Oil	216	246	261	4.5	53	High	0.7	0.07	1372
Safflower Oil	206	240	255	3.4	250	Very high	0.63	0.06	1235
Sesame Oil	213	316	258	6.3	480	Very high	0.65	0.08	1300
Jatropha Oil	208	240	273	4	57	High	0.5	0.07	1980
Sunflower Oil	206	328	255	5.5	300	Very high	0.68	0.07	1372
Neem Oil	135	248	264	7.2	200	Above average	0.5	0.07	1560
Palm Oil	245	304	249	15	53	High	0.38	0.09	1569
Mustard Oil	205	254	258	6.4	300	Above average	0.68	0.09	1235
Coconut Oil	165	320	251	31	190	Very high	0.54	0.08	1236
Karanja Oil	172	220	264	6.2	180	Average	0.5	0.05	1400
Soyabean Oil	219	254	264	2.5	85	High	0.69	0.05	1275
Cotton seed Oil	211	252	268	1.5	130	High	0.65	0.06	1569

VI: Viscosity Index, FP: Flash Point, PP: Pour Point, OS: Oxidation stability, C: Cost, A: Availability, AWSD: Anti-wear scar diameter, COF: Coefficient of friction and WL: Weld load.

In this paper, authors tried to assess the criticality in the selection of appropriate ecological base oil of vegetable plant seeds to be used for metal cutting operations. In Present work, fourteen vegetable base oils such as Castor oil (CO), Groundnut oil (GO), Rapeseed oil (RAPO), Safflower oil (SAFO), Sesame oil (SESO), Jatropha oil (JO), Sunflower oil (SUFO), Neem oil (NO), Palm oil (PO), Mustard oil (MO), Coconut oil (COCO), Karanja oil (KO), Soyabean oil (SOBO) and Cottonseed oil (COTO) were considered for decision making assessment, and nine attributes of corresponding vegetable base oils were included such viscosity index, flash point, pour point, oxidation stability, AWSD at 392N of load, COF, weld load, cost, and availability as depicted in table 1.

2.2 Preparation of the Decision Matrix

According to the problem statement, a study is done on attributes for various alternatives of vegetable base oils, and prepared decision matrix from available numerous data. Attributes are of two types, such as beneficial attribute which contain higher value and another one is a non-beneficial attribute, which contain a lower value. In this problem, VI, FP, PP, OS and WL belong to the beneficial attribute and C, A, COF and AWSD are non-beneficial. In decision matrix, all data must be quantitative for further simplified calculations. In the proposed problem, availability is the qualitative attribute, so

it was converted into a quantitative attribute by using a fuzzy logic method. Table 2 is recommended, which denotes the selection of attribute on a qualitative scale using fuzzy logic as derived by Chen and Hwang [24].

Table 2: Values of Selection Qualitative Attribute [24]

Qualitative Measures of Selection Attribute	Fuzzy Number	Crisp Score
Very Low	M-1	0.000
Low	M-2	0.136
Below average	M-3	0.318
Average	M-4	0.500
Above average	M-5	0.681
High	M-6	0.863
Very high	M-7	1.000

2.3 Normalization of Decision Matrix

All the numerous data in the decision matrix must be normalized to get same units of available attributes. By normalizing, we can consider all the attributes for evolution process. Decision matrix for defined problem is as depicted in the table 3.

Table 3: Data of the Base Oil Selection Attributes

	VI	FP	PP	OS	C	A	AWSD	COF	WL
CO	220	260	246	1.2	145	0.6818	0.15	0.09	2158
GO	214	249	270	6.5	250	1.0	0.63	0.04	1200
RAPO	216	246	261	4.5	53	0.8636	0.70	0.07	1372
SAFO	206	240	255	3.4	250	1.0	0.63	0.06	1235
SESO	213	316	258	6.3	480	1.0	0.65	0.08	1300
JO	208	240	273	4.0	57	0.8636	0.50	0.07	1980
SUFO	206	328	255	5.5	300	1.0	0.68	0.07	1372
NO	135	248	264	7.2	200	0.6818	0.50	0.07	1560
PO	245	304	249	15	53	0.8636	0.38	0.09	1569
MO	205	254	258	6.4	300	0.6818	0.68	0.09	1235
COCO	165	320	251	31	190	1.0	0.54	0.08	1236
KO	172	220	264	6.2	180	0.5	0.50	0.05	1400
SOBO	219	254	264	2.5	85	0.8636	0.69	0.05	1275
COTO	211	252	268	1.5	130	0.8636	0.65	0.06	1569

Attributes can be normalized by using equation (1),

$$y_{ij}^* = \frac{y_{ij}}{\sum_{i=1}^n y_{ij}} \quad (1)$$

where, y_{ij}^* is the normalized value of y_{ij} .

Normalized data of the base oil selection for alternatives is as shown in table 4

Table 4: Normalized Data of the Base Oil Selection Attributes

	VI	FP	PP	OS	C	A	AWSD	COF	WL
CO	0.0776	0.0697	0.0677	0.0119	0.0542	0.0575	0.0190	0.0928	0.1055
GO	0.0755	0.0667	0.0743	0.0642	0.0935	0.0843	0.0799	0.0412	0.0586
RAPO	0.0762	0.0659	0.0718	0.0445	0.0198	0.0728	0.0888	0.0722	0.0671
SAFO	0.0727	0.0643	0.0701	0.0336	0.0935	0.0843	0.0799	0.0619	0.0604
SESO	0.0751	0.0547	0.0710	0.0623	0.1796	0.0843	0.0825	0.0825	0.0635
JO	0.0734	0.0643	0.0751	0.0395	0.0213	0.0728	0.0634	0.0722	0.0968
SUFO	0.0727	0.0879	0.0701	0.0543	0.1122	0.0843	0.0863	0.0722	0.0671
NO	0.0476	0.0665	0.0726	0.0711	0.0748	0.0575	0.0634	0.0722	0.0762
PO	0.0864	0.0815	0.0685	0.1482	0.0198	0.0728	0.0482	0.0928	0.0767
MO	0.0723	0.0681	0.0710	0.0632	0.1122	0.0575	0.0863	0.0928	0.0604
COCO	0.0582	0.0858	0.0690	0.3063	0.0711	0.0843	0.0685	0.0825	0.0604
KO	0.0607	0.0590	0.0726	0.0613	0.0673	0.0421	0.0634	0.0515	0.0684
SOBO	0.0772	0.0681	0.0726	0.0247	0.0318	0.0728	0.0875	0.0515	0.0623
COTO	0.0744	0.0675	0.0737	0.0148	0.0486	0.0728	0.0828	0.0619	0.0767

2.4 Objective Weight of Attributes

Relative weight of attribute is calculated by the available data of the attribute in the decision matrix and normalized, subsequently. In proposed model, statistical variance is used for evaluating the objective weight of the attribute. Statistical variance measures, how far a data sets spread out. Variance can be calculated by using following equation (2),

$$V_j = \frac{1}{n} \sum_{i=1}^n \left(y_{ij}^* - (y_{ij}^*)_{\text{mean}} \right)^2 \quad (2)$$

where, V_j is the variance of the data relative to the j^{th} attributes and $(y_{ij}^*)_{\text{mean}}$ is the average value of y_{ij}^* . Variance values of nine attributes are as given in table 5.

Table 5: Variance Value of the Base Oil Selection Attributes

$[A_3]$	VI	FP	PP	OS	C	A	AWSD	COF	WL
	0.8623	0.08623	0.8622	0.8675	0.8641	0.8624	0.8626	0.8625	0.8624

Objective weight of the j^{th} attribute can be computed by statistical variance of the j^{th} attribute with summation of statistical variance for 'm' number of attributes. Objective weight of the j^{th} attribute can be calculated by equation (3),

$$w_j^o = \frac{V_j}{\sum_{j=1}^m V_j} \quad (3)$$

Objective weight of the attribute is computed as given in table 6.

Table 6: Objective Weight of the Base Oil Selection Attributes

$[A_4]$	VI	FP	PP	OS	C	A	AWSD	COF	WL
	0.1110	0.1110	0.1110	0.1117	0.1112	0.1110	0.1110	0.1110	0.1110

3. SUBJECTIVE WEIGHTS OF ATTRIBUTES

In this paper, subjective weight of attributes is decided using a scientific method such as Analytical Hierarchy Process. AHP is effective tool to solve complex type of problems. So, decision maker decide to utilize this tool to find out the best alternative. AHP is based on the relative importance weight of attribute over another attribute.

3.1 Pair Wise Comparison

Relative importance weight of attribute over other attribute is decided as per expert opinion and literature study. Pairwise comparison matrix is constructed by using Saaty's pair-wise comparison scale, as shown in table 7. An attribute compared with itself is assigned value 1, so in pairwise comparison matrix all diagonal values must be entered as 1, as shown in table 8.

Table 7: Saaty's Pair-Wise Comparison Scale

Strength of Importance	1	2	3	4	5	6	7	8	9
Definition	Equal importance	Weak	Moderate importance	Moderate plus	Strong importance	Strong plus	Very strong	Very, very strong	Extreme importance

Assuming square matrix $B_{M \times M}$ which is developed by the pairwise comparison of attribute i yield with attribute j , where b_{ij} indicates the relative importance weight of attribute i with respect to the objective or attribute j . In pairwise matrix $b_{ji} = 1$ when $i=j$ and $b_{ji} = 1/b_{ij}$

Table 8: Pair wise Comparison Matrix

	<i>VI</i>	<i>FP</i>	<i>PP</i>	<i>OS</i>	<i>C</i>	<i>A</i>	<i>AWSD</i>	<i>COF</i>	<i>WL</i>
$[A1] =$									
<i>VI</i>	1.00	0.14	0.17	0.11	0.13	0.14	0.17	0.20	0.14
<i>FP</i>	7.00	1.00	2.00	2.00	3.00	2.00	3.00	3.00	2.00
<i>PP</i>	6.00	0.33	1.00	2.00	2.00	2.00	3.00	2.00	3.00
<i>OS</i>	9.00	0.33	0.33	1.00	2.00	2.00	3.00	2.00	3.00
<i>C</i>	8.00	0.50	0.50	0.50	1.00	2.00	2.00	2.00	2.00
<i>A</i>	7.00	0.50	0.50	0.50	0.50	1.00	2.00	2.00	2.00
<i>AWSD</i>	6.00	0.33	0.33	0.33	0.50	0.50	1.00	3.00	3.00
<i>COF</i>	5.00	0.33	0.33	0.33	0.50	0.50	0.33	1.00	3.00
<i>WL</i>	7.00	0.50	0.33	0.33	0.50	0.50	0.33	0.33	1.00

3.2 Relative Normalized Weight (W_j)

To find the relative normalized weight of attribute, first calculate the geometric mean of the i^{th} attribute by using equation (4) and then normalize the geometric mean of rows in the pairwise matrix by using equation (5).

$$GM_j = \left[\prod_{j=1}^M b_{ij} \right]^{\frac{1}{M}} \quad (4)$$

$$[GM_j] = \begin{bmatrix} 0.1857 \\ 2.4147 \\ 1.8644 \\ 1.6007 \\ 1.3566 \\ 1.1478 \\ 0.9266 \\ 0.7132 \\ 0.6077 \end{bmatrix}$$

The Geometric mean method has simplicity nature, easy to find out the maximum Eigen value and reduction in variation of results so that, in AHP geometric method, generally used to find the relative normalized weights of attributes. Total relative normalized weight is shown in table 9.

$$w_j = \frac{GM_j}{\sum_{j=1}^M GM_j} \quad (5)$$

Table 9: Total Relative Normalized Weight Matrix A2

$w_j = [A2] =$	0.0172
	0.2232
	0.1724
	0.1480
	0.1254
	0.1061
	0.0857
	0.0659
	0.0562

It is considered as; if summation of all the total relative normalized weights is equal to one, then the problem solving approach is going in right direction. Here, summation of matrix A2 is equal to 1 so, we are following right path towards the problem solving.

3.3 Calculate Matrix A3 and Matrix A4

Matrix A3 is calculated by taking product of Pairwise comparison matrix (A1) and Total normalized weigh of attribute (A2) as following equation (6),

$$A3 = A1 \times A2 \quad (6)$$

$$[A3] = \begin{bmatrix} 0.1605 \\ 2.1396 \\ 1.6661 \\ 1.4547 \\ 1.1622 \\ 0.9763 \\ 0.8519 \\ 0.6458 \\ 0.5610 \end{bmatrix}$$

Matrix A4 is the ratio of matrix A3 to matrix A2 as following equation (7),

$$A4 = \frac{A3}{A2} \quad (7)$$

$$[A4] = \begin{bmatrix} 9.3536 \\ 9.5848 \\ 9.6668 \\ 9.8308 \\ 9.2675 \\ 9.2011 \\ 9.9455 \\ 9.7947 \\ 9.9861 \end{bmatrix}$$

3.4 Determine the Max Eigen Value ($\lambda_{\max}$)

Max Eigen value ($\lambda_{\max}$) is the average value of Matrix A4.

Hence,

CI is directly promotional to deviation from the consistency. Consistency index is calculated by using following equation (8),

$$CI = \frac{(\lambda_{\max} - M)}{(M - 1)} \quad (8)$$

$$CI = 0.0782$$

3.6 Calculate the Random Index (RI)

Random index is obtained for the number of attributes used for decision making. These values are given by Saaty (1994) as table 10.

Table 10: Random Index (RI) Values [25]

Attributes	3	4	5	6	7	8	9	10
Random Index	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

Hence, the random index value (RI) for 9 attributes is 1.45

3.7 Consistency Ratio (CR)

Consistency Ratio (CR) is calculated by using equation (9),

$$CR = \frac{CI}{RI} \quad (9)$$

$$CR = \frac{0.0782}{1.45} = 0.0539$$

The result of this equation is acceptable when its value is equal to or less than 0.1. So, during preparation of initial matrix, there is stability in choosing weightages.

4. INTEGRATED WEIGHT OF ATTRIBUTES

As per the literature study, it is found that integration of objective and subjective weight will be more effective. So in this case, decision maker utilizes objective and subjective weight of attributes, and then utilize them to calculate integrated weights as per equation (10).

$$w_j^i = W^O w_j^O + W^S w_j^S \quad (10)$$

Where, w_j^i is the integrated weight of attributes and W^O and W^S are weightings given to the objective weight and subjective weights, respectively, and values of W^O and W^S are between 0 to 1.

4.1 Computation of Preference Index

Preference index generate the rank according to the characteristics of alternative. It indicates the rank of each alternative with respect to other alternative. Computation of preference index needs the summation of beneficial and non-beneficial attributes. PI can be computed for objective, subjective and integrated weight of attribute by following equation (11), (12) and (13), respectively.

$$P_i^O = \sum_{j=1}^m w_j^O y_{ij}^{**} \quad (11)$$

$$P_i^S = \sum_{j=1}^m w_j^S y_{ij}^{**} \quad (12)$$

$$P_i^i = \sum_{j=1}^m w_j^i y_{ij}^{**} \quad (13)$$

Beneficial attribute indicates higher value and non-beneficial attributes indicates lower value. Determination of beneficial attribute and non-beneficial attribute are calculated by using equation (14) and (15), respectively.

$$y_{ij}^{**} = \frac{y_{ij}^{*b}}{\left(y_{ij}^{*b}\right)_{\max}} \quad (14)$$

$$y_{ij}^{**} = \frac{\left(y_{ij}^{*nb}\right)_{\min}}{y_{ij}^{*nb}} \quad (15)$$

Where, y_{ij}^{*b} and y_{ij}^{*nb} refers the beneficial and non-beneficial values from normalized data and $\left(y_{ij}^{*b}\right)_{\max}$ designate the maximum value from beneficial attribute and $\left(y_{ij}^{*nb}\right)_{\min}$ designate the minimum value from non-beneficial attribute. Preference index computed for base oil alternative by objective, subjective and integrated weights of attributes is shown in table 11.

Table 11: Computation of Preference Index

Sl. No	Base oil (Alternatives)	Objective Weights	Subjective Weights	Integrated Weights (S 0.2 O 0.8)	Integrated Weights (S 0.5 O 0.5)	Integrated Weights (S 0.8 O 0.2)
1	Palm oil	0.7186	0.7437	0.7236	0.7311	0.7387
2	Castor oil	0.6855	0.6483	0.6780	0.6669	0.6557
3	Jatropha oil	0.6672	0.6624	0.6662	0.6648	0.6633
4	Rape seed oil	0.6368	0.6475	0.6389	0.6421	0.6453
5	Coconut oil	0.6333	0.7128	0.6492	0.6730	0.6969
6	Karanja oil	0.6200	0.6160	0.6192	0.6180	0.6168
7	Soya bean oil	0.6137	0.6110	0.6132	0.6124	0.6116
8	Groundnut oil	0.5927	0.5832	0.5908	0.5879	0.5851
9	cotton oil	0.5851	0.5797	0.5840	0.5824	0.5808
10	Neem oil	0.5663	0.5944	0.5719	0.5803	0.5887
11	Sunflower Oil	0.5615	0.5924	0.5677	0.5770	0.5863
12	Sesame oil	0.5468	0.5765	0.5528	0.5617	0.5705
13	Mustard oil	0.5452	0.5610	0.5484	0.5531	0.5579
14	Safflower oil	0.5336	0.5312	0.5331	0.5324	0.5317

Preference index, which shows highest value for corresponding alternative, will be the best choice among all alternatives shown as in figure 2.

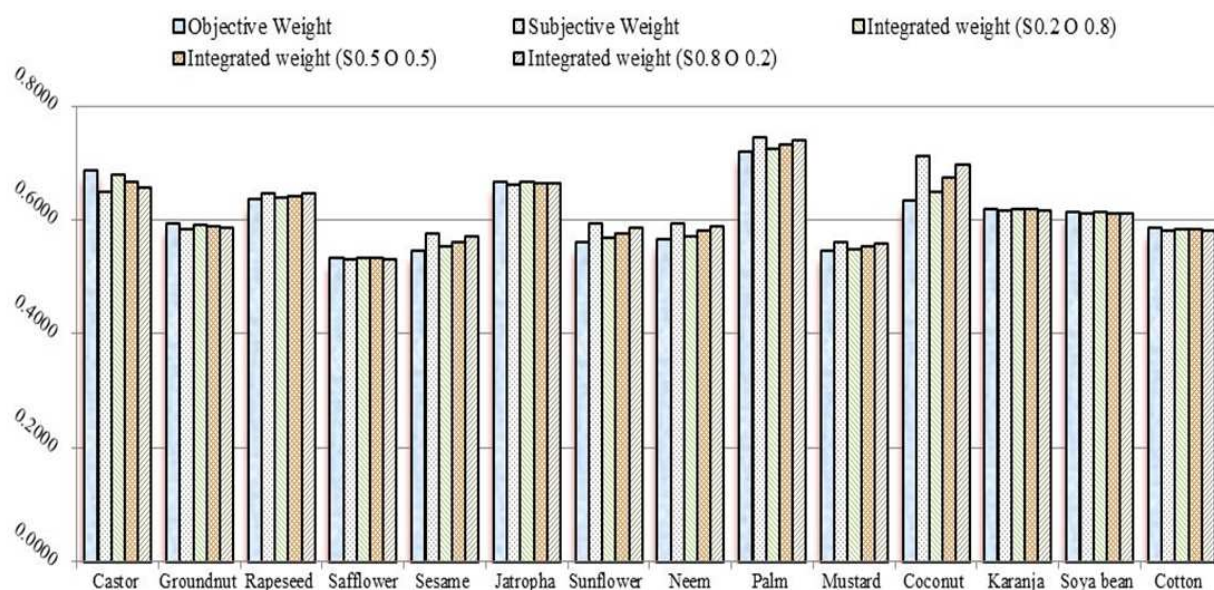


Figure 2: Overall Ranking of Alternatives.

5. CONCLUSIONS

In this paper, a novel scientific approach i.e. Multi-attribute decision making (MADM) model was applied for a complex problem of bio-based base oil selection, considering qualitative and quantitative attributes. Fourteen alternatives and their relevant nine attributes were evaluated by using MADM technique and AHP were used for evaluation of subjective weight and its performance index through all alternatives. Total weights above 0.6 are considered for further process, and it was found that palm oil is showing the highest weight, hence ranked number one followed by coconut oil, jatropha oil, castor oil and rapeseed oil. However, other base oils need to be formulated using a novel set of additives for their improved performance. The model proposed by the author, in this paper, guides to the decision maker to select appropriate base oil and further lead to the development of environment friendly base oil for metal cutting operation.

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